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Research on Optical Communication Technologies and Applications in Satellite Systems

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Abstract

A systematic review of the architectural framework, key technological breakthroughs, and future development trends in satellite optical communication is presented in this paper. An analysis of the limitations of conventional radio frequency (RF) communication in fulfilling the increasing demands for high data rates, large capacity, low latency, and high reliability in space-based applications is needed. This study emphasizes that laser communication, which has exceptional advantages such as ultrawide bandwidth, strong anti-interference capability, low power consumption, and high security, has become a strategic focal point in international space communication development. The composition and working principles of satellite optical communication systems are expounded upon. Case studies regarding low-Earth orbit (LEO) satellite networks and deep-space exploration communication links are utilized to examine key design considerations and performance constraints across diverse application scenarios. At the core technological level, an analysis of the principles, recent advancements, and challenges of several critical technologies is carried out, including high-power lasers with advanced modulation, high-sensitivity reception, precision beam pointing – acquisition – tracking (PAT), atmospheric channel compensation, and Doppler shift compensation. Emerging research frontiers, such as AI-driven dynamic link optimization, integrated space – air – ground optical networks, intelligent adaptive modulation, and the integration of quantum communication, are emerging. This work offers a theoretical basis and technical reference for constructing global, efficient, and reliable space information networks.

Keywords

satellite, optical communication, laser

1. Introduction

In domains such as deep-space exploration, global broadband access, and integrated space-ground information services, satellite communication assumes an irreplaceable position. The application scenarios are undergoing continuous expansion. Communication systems, in terms of transmission rate, capacity, latency, reliability, and power consumption, are confronted with ever-more stringent demands. Traditional radio-frequency technologies, such as those functioning in the C-band and Ku-band, are increasingly insufficient to buttress the advancement of future space-based information systems. This situation can be attributed to limitations in available spectrum resources (Hao et al., 2016), restricted bandwidth, high energy consumption, and innate signal propagation delays (Zhang et al., 2025).

In this context, laser communication technology has come to the forefront as a crucial breakthrough and a strategic development path within international space communications. Its notable merits include ultralarge bandwidth, robust anti-interference capabilities, low power consumption, high security levels, and a compact terminal layout. Optical communication employs laser beams as information conveyors, presenting copious available spectrum resources that extend from the visible to the infrared bands (for example, 850 nm and 1550 nm). The theoretical bandwidth is capable of reaching several hundreds of THz, surpassing that of traditional microwave communication by more than ten thousand times, thus establishing a firm basis for attaining single-link Tbps-level transmission speeds. This vast bandwidth enables real-time transfer of 8K/16K ultrahigh-definition video, high-resolution remote sensing data, and scientific payload data. Additionally, the high directivity and extremely narrow beam divergence of lasers substantially decrease transmission power consumption, enhance energy efficiency, and offer strong resistance to electromagnetic interference and eavesdropping. These attributes render laser communication especially appropriate for stable data transmission in demanding outer-space settings, such as those with intense radiation and high-particle interference.

Recently, multiple space undertakings have effectively manifested the viability of satellite laser communication. SpaceX's Starlink initiative (SpaceX commences deployment of starlink satellite internet constellation, 2019), for instance, has positioned a multitude of satellites furnished with laser terminals. It has established a global network featuring transmission latencies beneath 25 ms and data rates attaining Gbps magnitudes. China's "Hongyun Project" (Zhang et al., 2019) analogously employs 1550 nm laser communication to realize multidimensional high-speed connectivity among LEO satellites, ground facilities, high-altitude unmanned aerial vehicles, and 5G base stations. With respect to deep space exploration, NASA's deep space optical communication (DSOC) endeavor has achieved high-speed data transfer across tens of millions of kilometers at rates of hundreds of Mbps (Wollman et al., 2024). China's "Queqiao" relay satellite has also successfully accomplished stable video transmission at rates of up to 10 Mbps across the Earth - Moon expanse (Zhang et al., 2019). These achievements indicate that satellite laser communication is steadily advancing toward engineering actualization and practical utilization.

The present article systematically scrutinizes the application setting, pivotal technological breakthroughs, and forthcoming tendencies of optical communication within satellite systems. By inspecting the central bottlenecks inherent in traditional RF communication for aerospace applications, the architecture and operational procedure of satellite optical communication systems can be delineated. An in-depth dissection is then presented, covering key subtechnologies such as the modulation of high-power narrow-linewidth lasers (Shi et al., 2022) and the suppression of damage (Chen et al., 2024); the performance manifested by superconducting nanowire single-photon detectors (SNSPDs) in the reception of ultraweak light (Wollman et al., 2024); the structure and functionality of fast steering mirrors (FSMs) within high-precision tracking systems (Zhu et al., 2023); and real-time compensation mechanisms for atmospheric turbulence and attenuation (Chang et al., 2024), along with research headway and engineering implementations in the compensation of Doppler frequency shifts (Zhang et al., 2021).

2. Overview and Applications of Satellite Optical Communication Systems

2.1 System Composition and Working Principle

Opto-mechatronic systems of high integration, satellite optical communication systems, mainly consist of three subsystems: the optical channel, the receiver, and the transmitter. Key components such as lasers, optical antennas, and modulators are included in the transmitter. Electrical signals are converted into optical signals by the modulator via schemes such as phase, intensity, and frequency modulation, with advanced formats such as OFDM and QAM being increasingly utilized. For beam collimation and expansion, optical antennas usually adopt the structures of Cassegrain (Masoomi et al., 2024) or refractive telescopes (Huang et al., 2025), generating highly directional beams with extremely narrow divergence angles.

An optical receiving antenna, a detector, and a demodulator compose the receiver. The sensitivity is directly affected by the aperture size of the receiving antenna. Avalanche photodiodes (APDs) and PIN photodiodes are detectors that are commonly used. Superconducting nanowire single-photon detectors (SNSPDs), however, find application under conditions of extremely low light. Sophisticated signal processing algorithms are needed for the demodulator to suppress noise and interference.

Free-space propagation and atmospheric transmission are components of the optical channel. In free space, laser beams, despite almost linear propagation, experience divergence resulting from diffraction. Molecular absorption, aerosol scattering, and turbulence effects significantly impact the atmospheric channel. Intensity scintillation, phase fluctuation, and beam wandering, induced by turbulence, are principal factors that deteriorate communication quality.

Three stages, namely, link establishment, signal transmission, and link maintenance, are involved in the operation of the system. Initially, targets are acquired by a wide-field capture system and subsequently transferred to a narrow-field tracking mechanism for precise alignment. Signals are subject to modulation, transmission, reception, and demodulation processes. The application of real-time feedback control aims to maintain link stability. In the calculations of the link budget, the transmit power, antenna gain, path loss, and receiver sensitivity must be considered comprehensively. In satellite-to-ground links, free space loss can reach a value within the range of 200–300 dB, and atmospheric loss might exceed 20 dB under adverse weather conditions (Zhong et al., 2024). It is essential to reserve a sufficient margin to account for uncertainties.

2.2 Low Earth Orbit Satellite Internet Broadband Access

Satellites in the low Earth orbit (LEO), operating at altitudes within the 500–2000 km range, signify a flagship manifestation of satellite optical communications. This is attributable to their low latency and relatively minimal path loss. Projects such as SpaceX's Starlink (SpaceX commences deployment of starlink satellite internet constellation, 2019) and OneWeb have plans for the deployment of constellations consisting of thousands of satellites. The aim is to offer global broadband coverage. Starlink satellites are equipped with four laser communication terminals. These terminals support intersatellite links at speeds surpassing 10 Gbps and with latency below 25 ms. The performance they deliver is comparable to that of terrestrial fiber-optic networks. China's "Hongyun" project makes use of a 1550 nm laser with coherent BPSK modulation. It achieves a 2.5 Gbps transmission rate, a tracking accuracy below 5 μrad, and a bit error rate better than 10^{-6}.

Among the key technical hurdles in LEO satellite optical communication lies the high relative velocity between satellites and ground stations. This situation mandates frequent link handovers and reacquisition and imposes stringent requirements regarding the agility and stability of the tracking system. Efficient routing and management mechanisms are needed for large-scale satellite networks. Compensatory technologies such as adaptive optics are needed because of significant atmospheric effects. Moreover, accurate frequency offset estimation and compensation algorithms are required because of substantial Doppler shifts.

Solutions of diverse types have been proposed by researchers in an attempt to address these issues. With respect to pointing and tracking, adoption of a hybrid coarse–fine strategy occurs. Initial acquisition and large disturbances are managed by coarse tracking, with fine tracking carrying out precise adjustments. In the context of networking, software-defined networking (SDN) architectures make flexible scheduling of traffic and allocation of resources possible. For the purpose of augmenting robustness, forward error correction (FEC) coding is integrated with adaptive modulation to dynamically adjust system parameters in accordance with channel conditions.

2.3 Deep Space Exploration Optical Communication Links

The demands imposed on communication systems by deep space exploration are extreme in nature. Transmission distances can reach magnitudes of hundreds of millions of kilometers, signal levels are incredibly feeble, and delays may last several hours. Traditional RF communication encounters notable limitations within this scenario. For example, NASA's Mars rovers manage to attain maximum data rates merely on the order of several Mbps. These rates prove insufficient for the transmission of high-definition videos or substantial quantities of scientific data. Optical communication, however, presents a potentially viable alternative.

The 1550 nm laser utilization within NASA's DSOC project led to 267 Mbps transmission spanning 31 million kilometers. The sensitivity was at the single-photon magnitude, and the pointing precision was in the nanoradian range. Employing a dual-wavelength design (1550 nm for transmission and 1064 nm for tracking) with microradian tracking accuracy, China's "Queqiao" relay satellite achieved an Earth–Moon transmission rate of 1.2 Gbps. BPSK modulation and adaptive optics are utilized by the European Space Agency's EDRS system, which has a transmission rate of 1.8 Gbps.

Deep-space optical communications face major challenges. The signal power, which is extremely weak, has received power at a magnitude of approximately 10^{-18} W. The transmission delays are long, ranging from tens of minutes to several hours. Doppler shifts are significant, with relative velocities reaching up to kilometers per second. Pointing requirements are demanding, necessitating the control of tracking errors within microradians.

The subsequent technologies are essential for overcoming these challenges. High-power lasers and large transmitting antennas aimed at power augmentation. High-sensitivity detectors such as SNSPDs. Efficient coding and modulation for improving power efficiency. High-precision tracking and prediction algorithms to counteract platform motion. Future advancements will focus on higher-power lasers, novel modulation and coding configurations, advanced tracking algorithms, and integrated quantum communication, providing robust sustenance for humanity's cosmic exploration.

3. Breakthroughs in Key Technologies and In-Depth Analysis

3.1 High-Power Lasers and Advanced Modulation Techniques

Lasers characterized by high power and narrow linewidths have a determining influence on the transmission distance and capacity within the domain of satellite optical communications. Fiber lasers, which are recognized for their high efficiency, excellent beam quality, and dependable thermal management, have emerged as a principal area of research focus. Findings from studies suggest that spectral broadening techniques based on higher-order phase modulation are capable of significantly enhancing both the output power and linewidth performance. Experimental outcomes have shown that output powers surpass 100 W, accompanied by linewidths beneath 1 kHz, thus fulfilling the requirements for long-distance intersatellite links (Shi et al., 2022). The attainment of frequency stability on the order of 10^{-15} can be accomplished via techniques such as Pound–Drever–Hall (PDH) locking and optical phase-locked loops. Additionally, radiation-hardened designs ensure long-term orbital operation through the optimization of materials and structures.

For the enhancement of spectral efficiency, advanced modulation formats assume a position of significance. Schemes such as QPSK, 16QAM, 64QAM, and OFDM have been extensively adopted. OFDM, however, grapples with challenges associated with a high peak-to-average power ratio and susceptibility to nonlinear effects. Recent developments, encompassing DFT-spread OFDM and filtered multitone modulation, have successfully mitigated these problems. In the domain of deep-space communications, pulse position modulation (PPM) garners preference because its near-Shannon ability limits power efficiency. For example, the DSOC project uses 16 PPM to achieve reliable communication under conditions of a low signal-to-noise ratio. Alternative methods such as polarization modulation and compressed modulation also exhibit potential in the balancing of power and spectral efficiency.

3.2 High-Sensitivity Reception: From Coherent to Single-Photon Detection

The maximum communication distance and performance limits' determinant, a fundamental factor, is receiver sensitivity. Through mixing with a local oscillator, coherent detection converts the optical signal to the electrical domain, achieving near-quantum-limited sensitivity. A 3–6 dB sensitivity improvement over direct detection is offered by homodyne coherent reception, rendering it suitable for medium- to long-range intersatellite links. However, stringent requirements on the laser linewidth, phase noise, and digital signal processing algorithms are imposed.

In scenarios where illumination is extremely feeble, single-photon detectors assume a position of nondispersensitivity. NASA's deep-space communication projects (Wollman et al., 2024) have witnessed the deployment of superconducting nanowire single-photon detectors (SNSPDs). These detectors possess near-unity detection efficiency, low dark count rates (<100 Hz), and picosecond-scale timing resolution. Moreover, alternatives such as InGaAs-based avalanche photodiodes (APDs), upconversion detectors, and quantum dot detectors are undergoing advancements. Regarding signal processing, advanced forward error correction (FEC) schemes, with LDPC codes and polar codes being part of them, significantly increase system sensitivity. The

DSOC project is taken as an example. It makes use of a concatenated coding scheme that combines LDPC with an outer repetition code. This enabled the achievement of a bit error rate beneath 10^{-6} in the context of extremely low signal-to-noise ratios.

3.3 Precision Beam Pointing, Acquisition and Tracking (PAT)

Satellite optical communication encompasses the technology of pointing, acquisition, and tracking (PAT), a domain replete with both cruciality and challenges. Ultralong transmission distances, in conjunction with extremely narrow beam divergence angles, impose a requirement for pointing accuracy at the microradian echelon. Take, for example, GEO - LEO links; here, the constraint is to control pointing deviations within a few centimeters. Employing a multistage strategy, the acquisition process thus unfolds: initial pointing is gauged on the basis of orbital predictions and ephemeris data. Wide-field detectors are subsequently utilized for coarse acquisition. Ultimately, the system undergoes a transition to narrow-field precision tracking. The entire process can be accomplished within a span of tens of seconds.

Hybrid coarse–fine architectures are commonly embraced by tracking systems. Wide-range pointing is furnished by coarse tracking mechanisms, such as gimbals. High-bandwidth, small-scale corrections are attained via fine tracking, which hinges upon fast steering mirrors (FSMs) or MEMS mirrors. Research findings indicate that platform vibration and thermal deformation can be effectively curbed by the combination of dual-loop control and adaptive algorithms (Zhu et al., 2023). Dual-wavelength designs are frequently employed by beacon systems. Predictive algorithms, such as Kalman filtering, are further needed in deep-space communications to offset motion errors engendered by long delays. Recently, machine learning and deep learning techniques have been integrated for vibration prediction, orbital compensation, and signal recognition within complex backgrounds, substantially increasing the precision and robustness of PAT systems.

3.4 Atmospheric Channel Compensation and Mitigation

The intensity scintillation, phase fluctuation, beam wandering, and degradation of primary sources in space-to-ground links are induced by atmospheric turbulence. The scintillation index, under strong turbulence conditions, can exceed 1, causing severe communication outages. Adaptive optics (AO), the primary compensation technique, uses wavefront sensors (e.g., Shack–Hartmann sensors) for real-time wavefront distortion detection and deformable mirrors (e.g., MEMS-based mirrors) for correction. AO systems, although capable of achieving kHz-range bandwidths, present challenges in terms of complexity and cost for space-borne applications.

Wavefront-sensorless adaptive optics, partially corrected adaptive optics, and machine learning-based turbulence prediction and compensation methods have been developed by researchers. This development aims to reduce system complexity, addressing these limitations. The decorrelation of optical signals across multiple apertures is exploited by spatial diversity techniques. Turbulence effects are thus mitigated; employing 4–6 diversity channels can notably increase link availability. Adaptive modulation and coding, OFDM, and automatic repeat request (ARQ) protocols (Verma and Mathur, 2021) increase robustness at the link layer. Operating within the 1.55 μm atmospheric window and utilizing circularly polarized light can alleviate polarization-related impairments. The system design should incorporate an adequate link margin for adverse weather conditions.

3.5 Doppler Shift and Compensation Techniques

In LEO - LEO links (Pita et al., 2022), relative satellite motion-induced Doppler shift can reach up to 10 GHz, and in satellite-to-ground scenarios, several GHz. Signal reception and carrier recovery are severely impacted. Precompensation based on orbital predictions, a simple and effective method demanding high-precision prediction, is typically employed by direct detection systems. Digital frequency offset estimation and compensation algorithms, such as fast Fourier transform (FFT)-based or pilot-assisted methods, which offer greater flexibility at the expense of computational complexity, are utilized by coherent detection systems. In deep-space communications, a hierarchical compensation strategy integrating radio-frequency and optical downconversion is adopted to manage extreme frequency offsets.

In the recent past, the application of machine learning techniques, neural networks and reinforcement learning to the learning of frequency shift patterns and the optimization of adaptive compensation parameters has taken place. This application has substantial advantages in dealing with nonlinear and time-varying challenges. With respect to system design, it is essential to guarantee sufficient receiver bandwidth, integrate frequency tracking algorithms, and embrace robust signal processing architectures. At the protocol level, frequency division multiple access and spread spectrum techniques are instrumental in lessening the impact of frequency offset.

3.6 Current Technical Limitations and Future Challenges

Despite considerable progress, satellite optical communication technology still faces multiple technical challenges and development bottlenecks, including insufficient device reliability, high system complexity, substantial costs, and a lack of standardized protocols.

The reliability of devices is a concern of primary significance. Environmental conditions that are harsh, such as space radiation, extreme temperature fluctuations, and high vacuum, pose ongoing threats to the stability and service life of optical components. Active devices, with lasers and detectors included, are especially susceptible, necessitating designs that are radiation-hardened, screening that is rigorous, and manufacturing processes that are reinforced. At present, the mean time between failures (MTBF) of key space-qualified optical communication components remains markedly lower than that of conventional RF devices, which significantly restricts the long-term orbital reliability of entire systems.

Another barrier of significance is cost. High-performance optical assemblies, precision tracking mechanisms, and radiation-hardened electronics, which are key components, are expensive by nature. System testing and validation rely on complex ground-based simulation platforms and specialized facilities, with a substantial increase in R&D and deployment expenses. The per-bit transmission cost might eventually be lower than that of RF systems. However, the high initial investment needed still obstructs widespread adoption.

The development on a large scale is further restricted by the absence of standardized protocols and interfaces. In aspects such as interface specifications, testing methodologies, and network protocols, satellite optical communication is lacking in unified standards. Different systems thus face challenges in interoperability. Even though international organizations, including ITUs, are vigorously advancing relevant standards, the overall advancement is still relatively sluggish.

Several fundamental scientific questions, in addition to these issues, require further investigation. Among them are real-time prediction and accurate modeling of atmospheric turbulence, effective compensation of nonlinear optical effects, and quantum-limited detection of extremely weak optical signals. Future technological breakthroughs and innovative developments in the field will hinge upon addressing these challenges.

4. Future development Trends and Research Frontiers

4.1 Dynamic Intelligent Link Compensation and Optimization Technology

The advancement of dynamic link compensation within satellite optical communications has been notably propelled by artificial intelligence. Traditional fixed algorithms frequently encounter challenges in adapting to intricate and variable spatial surroundings. Conversely, machine learning empowers real-time learning and precise compensation. A cross-layer topology control approach that integrates physical-layer impairment compensation and network-layer routing optimization was proposed by Zhang Yuan et al. This methodology dynamically modifies modulation schemes and transmission routes, leading to an increase in network throughput of more than 30% (Zhang, 2021). Deep learning techniques further enhance channel modeling and prediction. Convolutional neural networks (CNNs) are capable of extracting the spatiotemporal features of atmospheric turbulence. Recurrent neural networks (RNNs) delineate temporal correlations. Generative adversarial networks (GANs) generate synthetic data to offset measurement inadequacies. Adaptive parameter adjustment is facilitated by reinforcement learning via policy exploration, as illustrated by Alaluf et al. in their tip/tilt precompensation technique (Alaluf and Armengol, 2022). Federated learning, through its distributed training and parameter-sharing mechanisms, effectively balances data privacy and communication burden, rendering it especially appropriate for multinode satellite networks.

Collaboration among multiple agents, learning in an online environment, and optimization across layers will be the foci of future research endeavors. The incorporation of edge computing and digital twin technologies is anticipated to endow space optical networks with enhanced intelligence and autonomy.

4.2 Integrated Space–Air–Ground Optical Network Convergence

Optical communication technology, as the high-speed backbone, is what the integrated space–air–ground network, a core architecture within 6G mobile communication systems, depends upon. The system has a layered and heterogeneous structure. Wide-area coverage and relay services are provided by geostationary (GEO) satellites. Low-latency access is delivered by low Earth orbit (LEO) satellites. Coverage gaps are filled by high-altitude platforms (for instance, stratospheric balloons or unmanned aerial vehicles). The last-mile connectivity is completed by terrestrial networks. Optical communication is utilized for high-speed intersatellite links and satellite-to-ground backbone connections.

For protocol design, accounting must be performed for the distinctive characteristics of the spatial channel, which include long propagation delays, high bit error rates, and intermittent connectivity. The adoption of delay-tolerant networking (DTN) and multipath transmission techniques is common to increase reliability. Software-defined networking (SDN) and network function virtualization (NFV) are what resource management makes use of to attain flexible and dynamic resource allocation. Intelligent algorithms, on the other hand, carry out the optimization of configurations founded upon service requirements and real-time channel conditions. In the domain of security, the quantum key distribution (QKD) provides theoretical information—theoretic security. Physical layer security techniques play a role in further fortifying protection against eavesdropping.

In this domain, the process of standardization is actively advanced by international organizations such as the International Telecommunication Union (ITU). China's substantial engagement in global cooperative undertakings and its dedication to the establishment of a unified international standards framework.

4.3 Intelligent Adaptive Modulation Strategy

Owing to the unceasing surveillance of channel conditions, intelligent adaptive modulation technology effectuates the dynamic selection of optimal modulation formats and coding schemes, with the aim of maximizing either spectral efficiency or power efficiency. An adaptive modulation and demodulation scheme for LEO satellite networks was devised by Zhou Shilei et al., which efficiently augments system throughput and reliability (Zhou and Wang, 2025).

The acquisition of channel state information can be achieved via methods such as pilot signals, data-aided estimation, or blind estimation. In channels with rapid variations, the prediction of dynamic trends assumes significance. Machine learning algorithms, which learn from historical data, are capable of increasing the forecasting accuracy. Decision-making algorithms span from simple threshold-based approaches to globally optimized strategies based on optimization theory and include adaptive schemes founded on reinforcement learning. For implementation, seamless handover support and reconfigurable architectures are needed. Software-defined radio (SDR) technology provides a practical basis for these requirements.

Performance, through the joint determination of modulation patterns, power regulation, and routing tactics, is further enhanced via cross-layer optimization. End-to-end optimization becomes feasible because of deep learning, and online learning endows the system with the ability of continuous self-enhancement. Symbol-level regulation, multiparameter joint optimization, and service-aware operational frameworks will be the foci of future advancements.

4.4 Quantum Communication Integration

The major frontier of next-generation satellite optical communication is the incorporation of quantum communication technologies. The quantum key distribution (QKD), through the utilization of quantum mechanical tenets, attains unconditionally secure key exchange. Satellite platforms offer a feasible approach for global-scale quantum network coverage. The successful demonstration of satellite-to-ground QKD by China's Micius satellite has led to a key distribution across distances surpassing 1,200 km (Sun, 2017).

The challenges, such as the extreme faintness of quantum signals and their coexistence with classical communication systems, must be addressed by system integration. Mutual interference mitigation is achieved through wavelength allocation, time scheduling, and spatial isolation. Quantum repeater technology, which is founded upon quantum storage and entanglement swapping, has the capacity to surmount range limitations, with satellites functioning as relay nodes for the construction of global quantum networks. Quantum-enhanced communication techniques have the potential to exceed classical limits in domains such as imaging, sensing, and radar.

Efforts toward standardization are in progress. The industrial ecosystem is in a state of gradual maturation. High-speed satellite–ground QKD, hybrid quantum–classical networks, and the advancement of a quantum internet will be the foci of future research.

5. Conclusion

This paper provides a systematic review of the architectural framework, key technological advances, and development trends in satellite laser communication. The inherent limitations of conventional radio frequency technologies in meeting future demands for high data rates, large capacity, low latency, and high reliability in space-based information systems have been elucidated. Laser communication technology, with its ultrawide bandwidth, strong anti-interference capabilities, low power consumption, and high security, has emerged as a strategic development direction in international space communications.

Regarding system architecture. This paper focuses on the composition and operational principles of satellite optical communication systems. The technical characteristics of the three core modules are detailed: transmitter, receiver, and optical channel. Low-Earth orbit satellite broadband internet and deep-space exploration links were taken as representative cases. Different scenarios' critical design considerations and performance constraints were discussed.

With respect to the crucial technological echelon, the paper focuses on core domains. These include high-power narrow-linewidth lasers featuring advanced modulation, high-sensitivity reception, precision beam pointing–acquisition–tracking (PAT), atmospheric channel compensation, and Doppler shift compensation. In-depth analysis was provided regarding their technical tenets, research advancements, and engineering execution. Simultaneously, it pinpointed the persistent technical bottlenecks in device dependability, system intricacy, cost governance, and standardization.

Emerging research frontiers in satellite optical communications are outlined in this paper in a forward-looking manner. These include AI-driven dynamic link optimization, integrated space–air–ground optical networks, intelligent adaptive modulation, and quantum communication integration. Breakthroughs in these areas are anticipated to expedite the evolution of satellite optical communication toward enhanced intelligence, integration, networking, and security. Critical support for the construction of a global, efficient, and reliable space information network is thus provided.

For academic research and engineering practice within satellite optical communication, this study provides systematic technical guidance and a theoretical basis. Additionally, it offers support for decision-making in relevant technology development strategies. In future research, the focus should be on tackling key challenges. These include high-reliability device development, adaptive anti-interference transmission, cross-layer collaborative optimization, and technological standardization.

References

Alaluf, D. and Armengol, J. P., (2022). Ground-to-satellite optical links: how effective is an uplink Tip/Tilt pre-compensation based on the satellite signal? *CEAS Space Journal,* vol. 14, no. 2, pp. 227-238.

Chang, Y., Li, Q. and Zhang, J., (2024). Research on atmospheric attenuation compensation technology of high-frequency band microwave in long-distance transmission. *Frontiers in Computing and Intelligent Systems,* vol. 8, no. 1, pp. 116-118.

Chen, D. Z., Wei, C. F., Song, Z. Q., Zhang, J., Ye, Y. G., Wei, B., Ji, X., Wang, S. Y. and Sun, X. H., (2025). Internet of Things Network Architecture Based on GEO-LEO Two-Layer Satellite Network. *Mobile Communications,* vol. 49**,** no. 8, pp. 25-33.

Chen, J., Ma, M., Wang, C. Q., Wang, X., Cui, S. H., Liu, A. D. and Feng, L., (2024). Research on fiber fuse effect in narrow line-width lasers. *Optics & Optoelectronic Technology,* vol. 22**,** no. 06, pp. 13-17.

Decker, T., Gallezot, M., Kerstan, S. F., Paesano, A., Ginter, A. and Wormsbecher, W., (2025). Quantum key distribution as a quantum machine learning task. *npj Quantum Information,* vol. 11**,** no. 1, p. 140.

Hao, C. Y., Luo, C. and Liu, H., (2016). Recent developments in satellite communications. *Application of Electronic Technology,* vol. 42**,** no. 8, pp. 11-15,20.

Huang, Z. Y., Zhu, J. Q. and Wang, Y. X., (2025). Optimized design of the tube structure for a large-aperture refracting space telescope. *Infrared and Laser Engineering,* vol. 54**,** no. 3, pp. 303-313.

Kong, D. Y., (2024). Doppler frequency offset estimation and tracking algorithm based on PMF-FFT. *Yangtze River Information and Communication,* vol. 37**,** no. 6, pp. 1-3,8.

Masoomi, N., Zakery, A. and Afkhami, M., (2024). Design of a compact multispectral telescope consisting of a Cassegrain telescope and a concave elliptical grating. *Applied Optics,* vol. 63**,** no. 9, pp. 2195-2203.

Pita, T. C., Vieira, I. P. and Mello, D. A., (2022). Published. All-digital compensation of doppler shift in leo-leo optical inter-satellite links. *Signal Processing in Photonic Communications*, Maastricht, Netherlands. Optica Publishing Group, p. SpTu3G. 2.

Shi, M., Wu, Z., Li, J., Wu, Y., Yu, M., Sun, Y., Hu, W. and Yi, L., (2022). High-power narrow-linewidth fiber lasers using optical spectrum broadening based on high-order phase modulation of inversion probability-tuning sequence. *Optics express,* vol. 30**,** no. 6, pp. 8448-8460.

SpaceX commences deployment of starlink satellite internet constellation. (2019). *Aerospace Engineering,* vol. 28**,** no. 3, p. 2.

Sun, J. F., (2017). Development concept for laser communication systems in integrated space-ground information networks. *Telecommunications Science,* vol. 33**,** no. 12, pp. 18-23.

Verma, G. D. and Mathur, A., (2021). Performance improvement of FSO communication systems using hybrid-ARQ protocols. *Applied optics,* vol. 60**,** no. 19, pp. 5553-5563.

Wollman, E. E., Allmaras, J. P., Beyer, A. D., Korzh, B., Runyan, M. C., Narváez, L., Farr, W. H., Marsili, F., Briggs, R. M. and Miles, G. J., (2024). SNSPD-based detector system for NASA's Deep Space Optical Communications project. *Optics Express,* vol. 32**,** no. 27, pp. 48185-48198.

Xiang, K. H., (2019). *Hongyun Engineering Technology Verification System,* Beijing: China Aerospace Science and Industry Corporation Second Academy.

Zhang, L. H., Xiong, L., Sun, J., Gao, S., Wang, X. L. and Zhang, A. B., (2019). Technical characteristics of the relay communication satellite "Queqiao" for Chang'e-4 lunar farside exploration mission. *Scientia Sinica(Technologica),* vol. 49**,** no. 2, pp. 138-146.

Zhang, M., Chen, D.-X., Ruan, P., Liu, J., Fu, D.-Z., Zhao, J.-L. and Yang, C.-P., (2024). Deep-learning-assisted optical communication with discretized state space of structured light. *Chinese Physics B,* vol. 33**,** no. 12, p. 120304.

Zhang, Y., (2021). *Design and Simulation of Dynamic Link Compensation Based Cross-Layer Topology Control Method.* Master's Thesis, Xi'an University of Electronic Science and Technology.

Zhang, Y., Huang, Y. H. and Zhang, G. X., (2021). Published. OFDM doppler shift compensation in low - earth orbit satellite communication systems: A review. *Satellite Applications Professional Committee of the Chinese Society of Astronautics; Satellite Communications Committee of the China Institute of Communications. Proceedings of the 17th Satellite Communications Academic Conference*, Beijing, China. China Communications Society, pp. 165-170.

Zhang, Z., Yang, Y., Li, H., Geng, Z. and Ding, H., (2025). Ga-doped NiZnCu ferrite@ polyaniline/carbon nanotube ternary composites operating in the C-band and Ku-band exhibit tunable microwave absorption performance. *Journal of Materials Science*, pp. 1-26.

Zhong, H. C., Li, T., Li, G., Tian, B. and Li, W., (2024). Impact of rainfall and atmospheric molecules on the echo response of fuzes. *Journal of Ordnance Equipment Engineering,* vol. 45**,** no. 05, pp. 86-92.

Zhou, S. L. and Wang, L. N., (2025). Design and implementation of adaptive modulation and demodulation schemes in low-earth orbit satellite networks. *Wireless Interconnection Technology,* vol. 22**,** no. 3, pp. 39-42.

Zhu, W. H., Wang, Y. and Wang, Y. H., (2023). Research progress on the reliability of MEMS rapid-response mirrors for satellite laser communications. *Infrared and Laser Engineering,* vol. 52**,** no. 9, pp. 230-242.

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